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Hail Resistance of Roofing Products

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Hail Resistance of Roofing Products

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Hail Resistance of Roofing Products

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A test was developed for evaluating the hail resistance of roofings, in which synthetic hailstones (ice spheres) of various sizes were shot at roof assemblies at their free-fall terminal velocities. Indentations, granule loss and roofing fracture were observed. The following conclusions have been made from these results:

(a) All roofing materials have some resistance to hail damage, but as the size of the hail increases, a level of impact energy is reached at which damage occurs. This level lies in the range of 1½ to 2 inch (3.8–5.1 cm) hailstones for most prepared roofings.

(b) Because of the ways in which prepared roofings are applied, most products have areas of different vulnerability.

(c) The solidly supported areas of roofing tend to be the most resistant to hail damage.

(d) Heavier shingles tend to be more hail-resistant than Type 235 shingles.

(e) Weathering tends to lower the hail resistance of asphalt shingles.

(f) Built-up roofs on dense substrates tend to resist hail better than those on soft substrates.

(g) Built-up roofs made with inorganic felts tend to be more hail resistant than those made with organic felts.

(h) Coarse aggregate surfacing tends to increase the hail resistance of roofing.

Key words: Asphalt shingles; built-up roofing; hail; roofing; shingles; storm damage.

1. Introduction

Hail, as a destructive force of nature, has plagued man, his crops and his property since the very beginnings of civilization. By far the vast majority of hailstorms contain hailstones that are relatively small. These small stones can damage crops, but not roofings. However, every year there are a number of storms in which hailstones occur in the range of 1½ to 3 in. (3.8 to 7.6 cm), or more, in diameter.

In the United States, except on rare occasions, storms containing large hailstones are encountered in the States between the Appalachian and Rocky Mounains. While there is no evidence that the number of such storms has been increasing in recent years, the population has grown in this part of the country, more buildings have been constructed and, consequently, the incidence of building damage has increased.

It has been extremely difficult, for a number of reasons, to determine precisely the damage attributable to hail. The same storm fronts that spawn large hailstones contain high winds, not too infrequently of tornadic velocities. The short hail period is usually followed by torrential rains. Consequently, in the "post-mortem" analysis of building damage caused by a storm, the allocation of the causes cannot always be made. Therefore, the Weather Bureau Reports [1][1] usually lump these three causes of damage together , but where possible, have separated them.

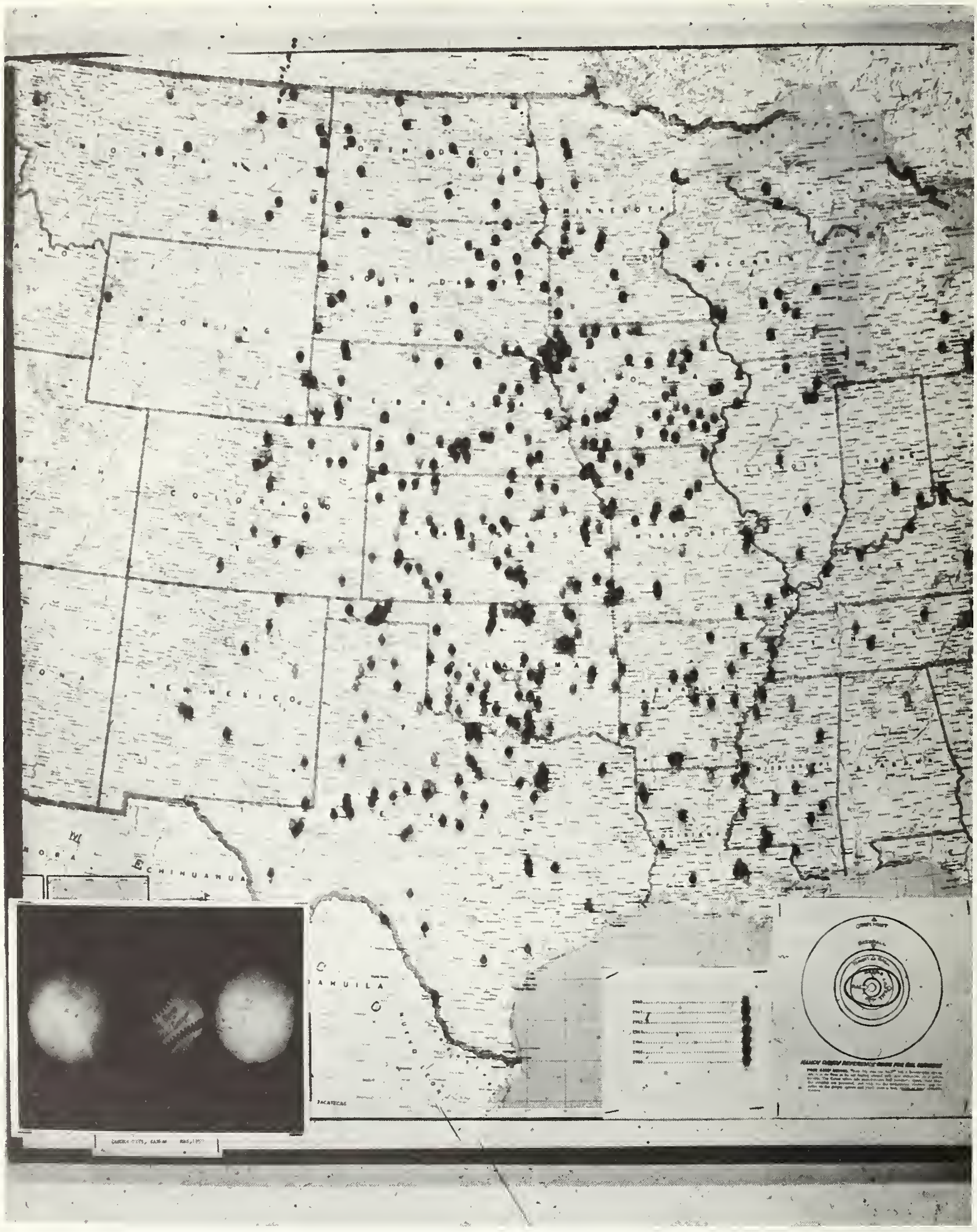
The hailstones in a storm are rarely of uniform size and, consequently, some damage remains hidden and does not appear until months or years later, in another storm, which might not be damaging on its own, or in cold weather, when ice penetration increases the destruction sufficiently to be observable. Even when only the damage unequivocally attributable to hail is considered, hail produces a greater annual loss through building damage than the more-spectacular tornado.

It is beyond the scope of this paper to discuss the theories of hail formation and growth, or storm development; this information may be found in references [2–6].

Two types of damaging hailstorms are encountered in the United States [5]. The most prevalent type is known as the frontal storm. It involves the encounter of a cold, high air mass with a low, moist, warm air mass. The cold air tends to fall and the warm, moist air tends to rise, carrying its moisture with it. The moisture cools through heat exchange with the cold air and evaporation as the air expands upward. Eventually it becomes cooled significantly below the freezing point and remains subcooled until it encounters a nucleus upon which to freeze. As more water hits any particular ice particle, the particle grows. Because everything in these upper regions is at a temveloped. It was conceded, following Laurie, that (1) ordinary impact tests were not satis-

[1] Figures in brackets indicate the literature references at the end of this paper.

perature much below the freezing point of water, the ice that forms does so rapidly and traps air in the process. This forms a milky layer of low-density ice. When an ice particle becomes too heavy to be raised farther by the updraft, it starts to fall. More condensation is collected during the fall, and once it reaches an area with temperatures above the freezing



Each pin represents a storm in which at least $5,000 worth of building damage was done by hail.

FIGURE 1. *Hail storm distribution map.*

point, the condensation on it is liquid water, and air can escape. This forms a layer of clear, high-density ice.

Sooner or later, the particle encounters another strong updraft, starts back up and freezes, subcools and goes through its tumbling cycle over and over again. Thus, the hailstone is found to consist of alternate layers of milky (low density) ice and clear (high density) ice. When the hailstone encounters no updraft sufficient to lift it, it falls to earth, usually at a velocity approximating the free-fall terminal velocity [9].

The second type of storm occurs on the eastern slopes of the Rocky Mountains; thus, it is called an orographic storm. A front of warm, moist air hits the base of the mountains, expands upward until the nucleation, freezing and tumbling processes occur and then the hailstones drop out as in the frontal storm. This type of storm tends to drop its hailstones at about 6000 ft.

Figure 1 is a map of the central United States showing the distribution of storms during the years 1960–1966 in which at least $5000 worth of building damage was done by hail in each storm. The orographic storms form an imperfect line at the left of the figure; the frontal storms account for the rest of the points. Only infrequently do building-damaging storms occur outside of this area.

Hailstorms occur all over the world in open regions where rapidly moving air masses can develop. However, only meteorological reports on storms and studies on the physics of hail formation can be found in the literature. Occasionally reports appear in the trade literature [7, 8] on hail damage to buildings, but only one paper has appeared in which a serious effort has been made to evaluate the effects objectively. In this paper [9], J.A.P. Laurie reported that he used 2½-in (6.4 cm) artificial hailstones, made by cutting cylindrical cores from blocks of ice, cutting them to heights equal to their diameter and molding them to roughly spherical shape. He fired these missiles at various velocities at building materials with a grenade launcher and determined the threshold energy of damage. The velocities were controlled by the size of the charge in the blank cartridges used in the launcher.

Because of the difficulties in controlling the velocities of the hailstones, an air-operated piston was developed and used as the launcher in the latter part of Laurie's study.

Laurie's paper, being the only one in its field, was the base from which this work was defactory, (2) the use of ice spheres was extremely desirable, if not absolutely necessary, (3) hail usually struck at its approximate free-fall terminal velocity (corroborated by others), and (4) a criterion for failure was damage that would permit the penetration of liquid water to an appreciable extent. However, it was decided to use a less complicated launcher, use "hailstones" of various sizes, cast the "hailstones" to approximate spheres more closely and explore areas of different vulnerability on various roofing systems. The work was primarily directed at bituminous roofing materials, but a sampling of other roofings was made.

2. Apparatus

2.1. Test Apparatus

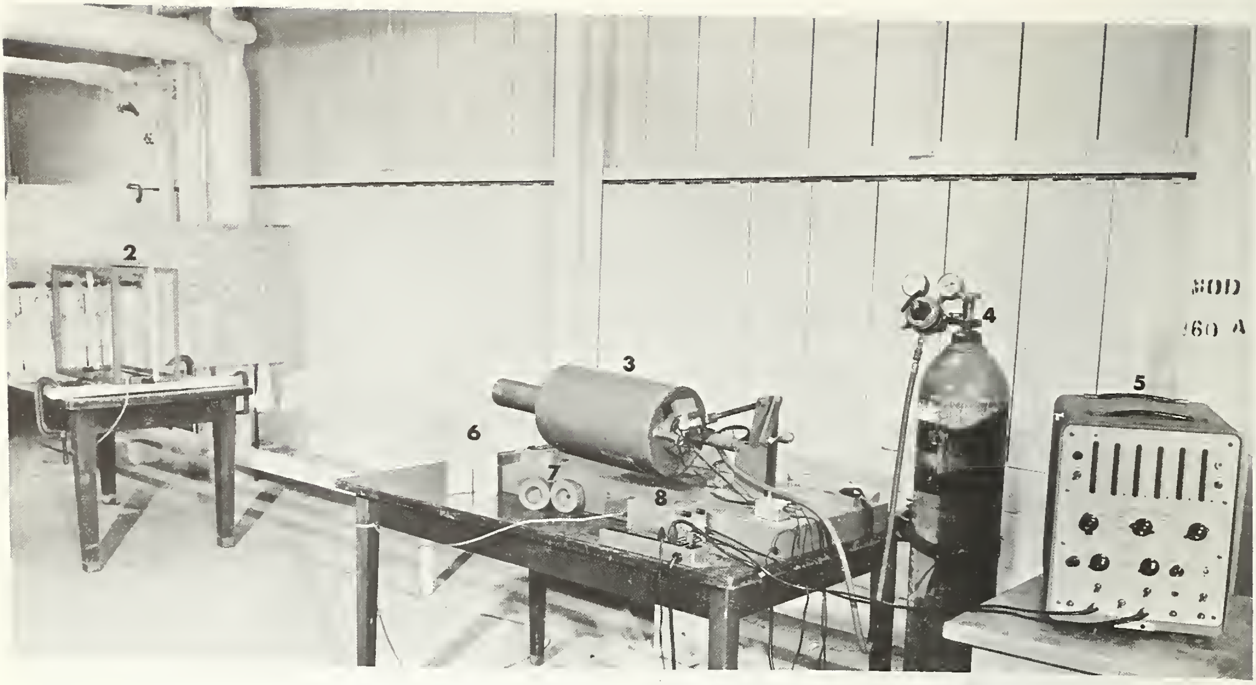
The apparatus consisted of a compressed air gun, for launching the hailstones, a timer, for determining their velocity, and a target area, for positioning the specimen to be tested. The physical layout of the apparatus is shown in figure 2.

The apparatus consisted of a specimen (target) area (1), timing range (2), gas gun (3), gas cylinder (4), timer (5), hailstone carrier (6), hailstone molds (7), and a triggering mechanism (8). The roofing specimen to be tested is mounted on a roof deck, just as in service, and clamped in place against the backstop in position (1). The timing range consists of a metal frame of ¾-in (1.9 cm) angle iron on which are mounted two microswitches 2.0 ft (61 cm) apart. The actuating levers on the microswitches contain metal hooks, which are used to hold one end of 1-in (2.5 cm) paper computer tapes, the other ends of which are fastened to the top members of the frames with masking tape, also 2.0 ft (61 cm) apart. The tapes are kept under tension such that any impact on them will close the microswitches and actuate the triggering mechanism to start and stop the counter (5).

The compressed air gun (4) is a commercially available device manufactured by Diamond King, Inc.[2] (El Segundo, Calif.). It is their Mark 14 model, with a 3¼-in (8.3 cm) inside diameter barrel and a maximum muzzle velocity of 300 ft/s (9144 cm/s). The counter is a Hewlett-Packard Model No. 523B microsecond counter, with both starting and stopping gates and a direct readout.

2.2. Hailstone Carriers

The hail carriers were made from 3-in (7.6 cm) diameter foamed polyethylene cylinders (Ethafoam—Dow Chemical Co., Midland, Mich.). This material was obtained as cylinders 9 ft (274 cm) long, sliced into short cylinders 6-in (15.2 cm) long and split in half longitudi-



The hail resistance of building materials was determined by shooting progressively larger hailstones at different parts of these materials until failure occurred.

1. Test specimen.
2. Timing section.
3. Compressed gas gun.
4. Gas cylinder.
5. Timer.
6. Hailstone carriers—one in gun and one in open to show cavity.
7. Hailstone mold.
8. Triggering mechanism.

FIGURE 2. *Hail resistance apparatus.*

nally (Item 6 fig. 2). Each hemicylinder was truncated at one end at 45 deg to its long axis from the central cut to its outer wall and milled with one of a series of sizes of hemispheres centered 2¼ in (5.7 cm) from its other end. Thus, when the two hemicylinders were reassembled, they formed carriers for the several sizes of hailstones and permitted one size barrel to be used for all of the hailstones. Carriers with recesses for 1½ (3.8 cm), 2 (5.1 cm), 2½ (6.4 cm) and 2¾ in (7.0 cm) hailstones were made. The 1¼-in (3.2 cm) hailstones were carried in the 1½-in (3.8 cm) carrier and the 1¾-in (4.5 cm) hailstones, in the 2-in (5.1 cm) carrier.

2.3. Hailstone Molds

The hailstones were cast in molds made from a silicone casting resin (RTV–60—General Electric Co.). The models for the hailstones were plastic fishing floats, which are produced in increments of ¼-in (0.6 cm) diameter from 1-in (2.5 cm) to 3-in (7.6 cm). Each float was suspended on the end of a rod, which fit the indentation in the float, in the center of a cylindrical polyethylene container of suitable size. The casting resin was deaerated, poured into the mold and cured. The following day the casting was removed from the polyethylene container and sliced through with a razor blade at a great circle of the float. The float and rod were removed and the cut interface covered with a thin layer of silicone grease.

The hailstones were cast in these molds in two stages, in order to permit expansion of water during freezing to occur without shattering the hailstones. Water was poured into the mold through the opening (called the gate) left by the removal of the suspending rod until the cavity (left by the float) was about one-half full and frozen in the freezing compartment of a conventional refrigerator. Four hours later water was added to fill the mold just to the bottom of the gate and the mold was returned to the freezer. Only by this two-stage process was it possible to freeze ice

2.4. Specimen Construction

The shingle specimens were applied with four staples (per strip) to 1 ft 6 in x 3 ft 0 in (46 x spheres without shattering. While the structure of these synthetic hailstones is different from that of naturally formed hailstones, it was felt that the differences in structure did not affect their performance.

[2] References to specific articles in the description of apparatus used in these experiments are for the purpose of definition of the experimental details, and should not be construed as preferential endorsements of these articles.

The ice spheres were stored in a chest-type freezer at about 10°F (—12°C) until ready for use.
91 cm) decks, representative of those used in construction (3/8 in (1 cm) and 1/2 in (1.3 cm) plywood, 1 in x 6 in (nominal) T & G boards). The decks were supported on 2–2 in x 4 in (nominal) "rafters," to which they were fastened 6 in (15.2 cm) from each of the short sides by 8d common nails. Thus, each deck represented a 1 ft 6 in x 3 ft 0 in (46 x 91 cm) section out of a conventional roof.

Wood, slate, asbestos cement, tile, and sheet metal roofing were applied as directed by their suppliers to decks supported on 2 in x 4 in rafters, 2 ft (61 cm) on centers.

The built-up roofing specimens, 1 ft (30.5 cm) square, were solidly mopped to 1/2 in (1.3 cm) plywood or 1 in (2.5 cm) asbestos cement board (to simulate a concrete deck) or to various types of insulation mopped solidly to these decks. Also, where metal decking was used, the insulation was mopped solidly to the decking.

3. Procedures

3.1. Shooting Hailstones at Roofing

The specimen on its deck was held against the backstop in figure 2 with large C clamps. The 1-in (2.5 cm) paper computer tapes were hooked to the microswitches and fastened to the top of the timing frame with masking tape. They were held under tension, just insufficient to close the switches. A hailstone of the desired size was taken from the freezer, cleaned of any burrs or projecting pieces of ice (from the gate in the mold), weighed, and placed in its carrier, which was slid into the barrel of the gun as far as possible. Air, or nitrogen, was permitted to enter the gun until the desired pressure was reached. The valves between the gun and the tank were closed (to protect the pressure regulator), the pressure gage was removed from the gun, and the gun was fired by opening the solenoid valve, which relieved the pressure behind the floating cylinder in the gun and permitted the remainder of the pressurized gas to escape into the barrel and expel the hailstone carrier.

The carrier was propelled out of the gun, where the air resistance opened the two halves and permitted the hailstone to travel alone toward the target. As the hailstone hit the first tape it started the counter, and as it hit the second tape, it stopped the counter. Then it hit the specimen.

The indentation on the specimen was measured and the condition of the specimen noted after each firing. A minimum of two hits in each area of vulnerability was observed and average values of damage used. Granule losses, coating and felt fractures and deck damage were recorded. The average velocities and energies of the hailstones in the 2 ft (61 cm) of travel immediately in front of the test specimen also were calculated and recorded.

3.2. Evaluating Failure

Damage to roofing by hail falls into two general categories: (1) Severe damage, which leads to penetration of the structure by the elements and (2) Superficial damage, which affects appearance but does not materially interfere with the performance of the roofing. While the latter is distracting and leads to insurance claims, the former is the type of damage that should be of most concern, because the possible loss can exceed the replacement cost of the roofing many fold. Thus, while the dents will be reported, only the fractures of the coating, felt or other shingle material will be called failure in this report. For each material and roofing system, the thresholds of failure, or the smallest hail size producing these failures, are reported.

4. Results

Although hailstones vary in size, shape, density, and velocity, those that do damage to buildings tend to fall within the narrow limits of ice spheres falling at about their free-fall terminal velocity [9].

The density of large hailstones has been shown to approximate that of solid ice [10] and seems to range between 0.89 and 0.91 g/cm^3. Hailstones, while rarely smooth spheres, can be treated aerodynamically as smooth spheres and conclusions reached are close to observed results [11]. The terminal velocities and energies of ice spheres have been calculated and reported graphically by Laurie [9]; they are tabulated below as taken from these graphs for the hailstone sizes used:

TABLE 1. *Terminal velocities and energies of hailstones*[a]

Diameter		Terminal velocity			Approximate impact energy	
inches	*cm*	*ft/s*	*mi/hr*	*(m/sec)*	*ft lbs*	*Joules*
1	(2.5)	73	50	(22.3)	<1	(<1.36)
1¼	(3.2)	82	56	(25.0)	4	(5.42)
1½	(3.8)	90	61	(27.4)	8	(10.85)
1¾	(4.5)	97	66	(29.6)	14	(18.96)
2	(5.1)	105	72	(32.0)	22	(29.80)
2½	(6.4)	117	80	(35.7)	53	(71.9)
2¾	(7.0)	124	85	(37.8)	81	(109.8)
3	(7.6)	130	88	(39.6)	120	(162.7)

[a] Read from graphs in reference [9].

All of the results reported are based on hailstones of a given size traveling at velocities within ± 10 percent of the terminal velocities reported in table 1 for hailstones of that size. The results are reported under the types of roofing studied.

4.1. Asphalt Shingles

When applied according to the recommendations of their manufacturers, Type 235 square-tab shingles have three regions of different vulnerability: (1) The tab edges, (2) The surface over the unsupported areas between the top of one strip and the "line" where the strip above it contacts the deck or underlayment, and (3) The triple coverage area solidly supported from the deck up [12].

The resistances of these areas to hail damage are different; therefore, results are reported for each area. The results for the Type 235 square-tab shingles are shown in table 2.

These specimens were also exposed to 1¼-in dentations were made in the shingles by the (3.2 cm) hailstones. Only small, superficial in-1¼-in (3.2 cm) hailstones. The larger size hailstones produced progressively larger dents. In general, the smaller hailstones produced circular indentations approximating one half their diameter and the larger hailstones, those above the felt-damage threshold, produced dents greater in diameter than one-half the hailstone diameter. Hailstones 2¾ in (7.0 cm) in diameter produced damage to the decks on which the shingles were mounted.

TABLE 2. *Hail resistance of Type 235 square tab shingles exposed 5 in (12.7 cm)*

Deck	Smallest hail size cracking shingle felt											
	No underlayment						15# Felt underlayment					
	Edges		Unsupported portion		Triple coverage		Edges		Unsupported portion		Triple coverage	
	in	*cm*	*in*	*cm*	*in*	*cm*	*in*	*cm*	*in*	*cm*	*in*	*cm*
⅜-in Plywood (1 cm)	1¾	(4.5)	1¾	(4.5)	1¾	(4.5)	1½	(3.8)	1½	(3.8)	1¾	(4.5)
½-in Plywood (1.3 cm)	1¾	(4.5)	1¾	(4.5)	1¾	(4.5)	1½	(3.8)	1½	(3.8)	1½	(3.8)
1 x 6 in nominal T&G	2	(5.1)	1¾	(4.5)	2½	(6.4)	1½	(3.8)	1½	(3.8)	2	(5.1)

Shingles on ⅜-in (1 cm) and ½-in (1.3 cm) plywood performed equally well; those on 1 x 6-in T & G roof boards were more resistant to hail damage than those on plywood.

The shingles without an underlayment consistently had a higher threshold of hail damage than did those with the conventional 15 lb saturated felt underlayment on all three decks. Apparently, the soft layer of felt makes the shingle slightly more vulnerable. The improved performance usually involved only ¼-in (0.6 cm) larger hailstones, but this represented resistance to 6.3 or 9.5 more foot pounds (8.5 or 12.8 joules) of kinetic energy. From these results, it would seem that the solidly supported roofings performed better than those with some soft underlying layer in their construction. This observation is consistent with the fact that shingle materials are stronger in compression than in tension and the best performance can be expected when the impact forces can be kept as pure compression forces. Any soft layer within the system permits the back of the layer above it to be in tension and fail more easily.

As shingles age during exposure they tend to undergo a number of physical changes, which may affect their resistance to hail. A number of shingles that had been exposed on ½-in (1.3 cm) plywood to the weather in Washington, D. C. for 9½ years became available and were tested. These shingles had been exposed at a 4-in pitch (10 cm in 30 cm) facing due south. Three different Type 210 shingles showed failures (felt cracking) on all three areas of different vulnerability with 1¼-in (3.2 cm) hailstones. One Type 255 and one Type 290 shingle experienced spalling of the coating with 1¼-in (3.2 cm) hailstones, but felt damage did not occur until 1½-in (3.8 cm) hailstones were used. Two Type 250 shingles showed felt damage in all three areas of vulnerability with 1¼-in (3.2 cm) hailstones; however, one Type 250 and one Type 275 shingle showed no damage below 1¾-in (4.5 cm) hailstones on the tab centers, but both developed felt damage in the other two areas with 1¼-in (3.2 cm) hailstones. No direct comparison can be made between these aged shingles and unexposed ones because of changes in design and production. However, the aged shingles tended to be less resistant to hail damage than the new ones.

A number of heavy weight and premium shingles were also investigated. Some of these resisted hail no better than the regular Type 235 square-tab shingles. However, a few performed significantly better, as discussed below.

A Class B shingle based on a glass fiber mat, instead of the conventional organic felt, did not show felt-type failure on its tab edges and unsupported areas with hailstones smaller than 2 in (5.1 cm). It failed with 2½-in (6.4 cm)

hailstones on the solidly supported areas. Similarly, three other shingles, all Class A, based on glass mat felts showed no felt damage on their obverse sides with hailstones below 2 in (5.1 cm) in diameter; one of these had a damage threshold at the 2½-in (6.4 cm) hailstone on all three portions of its surface. Some of the conventionally made heavy shingles, usually with Number 9 granules or with high concentrations of mineral additives, performed equally well. One Type 290 Class C shingle actually had a damage threshold at the 2¾-in (7.0 cm) hailstone. While it is outside the province of this report to identify these heavy Class C and Class A shingles more specifically, the manufacturers have been informed of how their individual products performed and the basic principles required to make more hail-resistant products. All of these shingles were mounted on ½-in (1.3 cm) plywood.

Because the vast majority of hailstorms occur in warm weather, the roofs are above ambient temperatures when the hailstorm starts. Hailstorms that produce large hailstones are always of short duration and are preceded by a cloud cover, which drops the roof temperatures below their daily highs. Therefore, the hail resistance evaluation was conducted at 75 to 80°F (24 to 27°C). However, one Type 235 and one Type 315 Class C shingle and one Type 240 Class A shingle were tested at 120°F (49°C) on a ½-in (1.3 cm) plywood deck with a 15 lb saturated felt underlayment. The hail resistance of the Type 235 shingle was increased to the 2½-in (6.4 cm) hailstones from the 1½-in (3.8 cm) hailstones on all three surfaces. That of the Type 315 shingle was improved only on the unsupported areas and that of the Type 240 was not changed. Thus, the results on these three shingles indicate that shingles tend to be more resistant to hail damage at higher temperatures. It is fortunate that hailstorms occur in warm weather.

4.2. Built-Up Roofs

Occasionally in residential construction and much more frequently in commercial and industrial construction relatively flat roofs are used. These roofs are not "factory manufactured," but "built up" on the site from alternate layers of bitumen and reinforcing membranes. Some of these roofs are surfaced with a smooth layer of bitumen and others are surfaced with a layer of pebbles, crushed stone or light weight aggregate particles in addition to a layer of bitumen. There are many variations of this type of roof system; only a few representative ones were tested. The construction of these roofs and the results of the hail-resistance tests are summarized in table 3.

The conventional smooth-surface built-up roof [1a and 1e in table 3] on a dense deck showed visible signs of damage; i.e., cracking of the surface, when 2-in (5.1 cm) hailstones were used. Smaller hailstones usually indented the flood coat, but did not crack it. When fiberboard (1b) or glass fiber (1g) insulation was installed between the deck and the roof membrane the indentations were larger and coating cracks appeared with 1¾-in (4.5 cm) hailstones. The roofing on Foamboard A insulation (1c) performed better than on the dense decks when 2-in (5.1 cm) hailstones were used, but 2½-in (6.4 cm) hailstones penetrated through the roofing into the insulation. Foamboard B (1d) delaminated; i.e., the insulation broke away from its protective asphalt coated felts, when impacted with 2-in (5.1 cm) hailstones. The roofing on glass fiber insulation (1g) on steel decking was penetrated by 2½-in (6.4 cm) hailstones.

The flood coat of the built-up roof made with asbestos felts on a plywood deck (2a) did not crack or become indented by 2½-in (6.4 cm) hailstones; however, the flood coat was indented and cracked by 2-in (5.1 cm) hailstones when fiberboard insulation (2c) was used between the membrane and the deck. The asbestos-felt roofs had better hail resistance than the rag felt built-up roofs on comparable decks.

The built-up roofs made with coal tar pitch [3], referred to as tar in table 3, did not indent, but developed concentric cracks with all sizes of hailstones. The 2½-in (6.4 cm) hailstones caused some of the flood coat to spall from the top felts [3a]. Coal tar pitch generally tends to be more brittle than asphalt and would be expected to respond to the hail impact as a brittle material.

The roofs built up with glass fiber felts on the dense decks (4a and 4b) (plywood and asbestos cement) did not experience flood coat cracking with hailstones 2½-in (6.4 cm) in diameter and smaller, but when insulation was present (4c, 4d, 4e, and 4f), cracks were produced with 2½-in (6.4 cm) hailstones. The glass felt roofs fell in between the organic felt built-up roofs and asbestos felt built-up roofs in hail resistance.

The roofs constructed of two base sheets (5) performed much better on the asbestos cement deck (5b) than on plywood (5a); their performance on plywood or insulation were about the same as conventional asphalt-organic-felt built-up roofs on the same substrates. Where these roofs were covered with 300 lbs/sq of slag (14.7 kg/m²) (6), no damage was done to the roof membrane by any of the hailstones. (The slag was retained by cheese cloth when the decks were tested in vertical positions). The hailstone energy was dissipated in scattering

TABLE 3. *Hail resistance of built-up roofs visual inspection*

Hailstone size, in (cm)	Hail damage indentation size [a]							
	1½	(3.8)	1¾	(4.5)	2	(5.1)	2½	(6.4)
	in	*cm*	*in*	*cm*	*in*	*cm*	*in*	*cm*
Roof construction								
(1) Base sheet+3 plies of 15 lb. organic felt+a 60 lb/sq (2.9 kg/m²) asphalt flood coat [20–25 lb/sq (1.0–1.2 kg/m²) interply asphalt] on								
(1a) ½-in (1.3 cm) Plywood	⅝	(1.6)	⅝	(1.6)	⅝	C[b] (1.6)	1¼ C	(3.2)
(1b) 1-in (2.5 cm) Fiberboard on ½-in (1.3 cm) plywood	⅝	(1.6)	1 C	(2.5)	1¼	C (3.2)	1⅝ C	(4.1)
(1c) 1-in (2.5 cm) Foamboard A on ½-in (1.3 cm) plywood	⅝	(1.6)	—		⅝	(1.6)	2¼ P	(5.7)
(1d) 1-in (2.5 cm) Foamboard B on ½-in (1.3 cm) plywood	¾	(1.9)	—		1¼	D (3.2)	—	
(1e) 1-in (2.5 cm) Asbestos cement	⅝	(2.2)	—		1	C (2.5)	1¼ C	(3.2)
(1f) 1-in (2.5 cm) Fiberboard on 22 Ga. steel decking	¾	(1.9)	⅝ C	(2.2)	1¼	C (3.2)	1¾ C	(4.5)
(1g) 1-in (2.5 cm) Glass fiber insulation on 22 Ga. steel decking	N		1 C	(2.5)	1¼	C (3.2)	2¼ FP	(5.7)
(2) Base sheet+3 asbestos felts+60 lbs/sq (2.9 kg/m²) asphalt flood coat [20–25 lbs/sq (1.0–1.2 kg/m²) interply asphalt] on								
(2a) ½-in (1.3 cm) Plywood	N		—		N		N	
(2b) 1-in (2.5 cm) Asbestos cement	N		N		1	(2.5)	N	
(2c) 1-in (2.5 cm) Fiberboard on ½-in (1.3 cm) plywood	N		N		1—	C (2.8)	—	
(3) Base sheet+3 tarred felts+75 lbs/sq (3.7 kg/m²) tar flood coat [25 lb/sq (1.2 kg/m²) interply tar] on								
(3a) ½-in (1.3 cm) Plywood	C		½ C	(1.3)	C		CS	
(3b) 1-in (2.5 cm) Asbestos cement	C		—		N		C	
(3c) 1-in (2.5 cm) Fiberboard on ½-in (1.3 cm) plywood	C		—		C		2 C	
(4) 2 Glass felts+1 glass cap sheet [20–25 lb/sq (1.0–1.2 kg/m²) interply asphalt] on								
(4a) ½-in (1.3 cm) Plywood	N		—		½	(1.3)	1	(2.5)
(4b) 1-in (2.5 cm) Asbestos cement	N		—		N		N	
(4c) 1-in (2.5 cm) Fiberboard on ½-in (1.3 cm) plywood	¾	(1.9)	—		1	(2.5)	1½ C	(3.8)
(4d) 1-in (2.5 cm) Fiberboard on 1-in (2.5 cm) asbestos cement	½	(1.3)	—		N		1½ C	(3.8)
(4e) ¾-in (1.9 cm) Glass fiber insulation on ½-in (1.3 cm) plywood	⅝	(1.6)	—		1⅛	(2.8)	1¾ C	(4.5)
(4f) ¾-in (1.9 cm) Glass fiber insulation on 1-in (2.5 cm) asbestos cement	½	(1.3)	—		⅝	(2.2)	1½ C	(3.8)
(5) 2 Base sheets+60 lbs/sq (2.9 kg/m²) asphalt flood coat [20–25 lbs/sq (1.0–1.2 kg/m²) interply asphalt] on								
(5a) ½-in (1.3 cm) Plywood	½ C	(1.3)	—		⅝	C (2.2)	1¼ C	(3.2)
(5b) 1-in (2.5 cm) Asbestos cement	N		—		N		N	
(5c) 1-in (2.5 cm) Fiberboard on ½-in (1.3 cm) plywood	¾ C	(1.9)	¾ C	(1.9)	1⅛	C (2.8)	—	
(5d) 1-in (2.5 cm) Fiberboard on 1-in (2.5 cm) asbestos cement	⅝ C	(1.6)	⅝ C	(2.2)	1 C	(2.5)	—	
(6) 2 Base sheets+60 lb/sq (2.9 kg/m²) flood coat+300 lb/sq (14.7 kg/m²) slag [20–25 lb/sq (1.0–1.2 kg/m²) interply asphalt] on								
(6a) ½-in (1.3 cm) Plywood	N		—		N		N	
(6b) 1-in (2.5 cm) Asbestos cement	N		—		N		N	
(6c) 1-in (2.5 cm) Fiberboard on ½-in (1.3 cm) plywood	N		—		N		N	
(6d) 1-in (2.5 cm) Fiberboard on 1-in (2.5 cm) asbestos cement	N		—		N		N	

[a] Mean diameter of indentation.
[b] C, Surface cracked. D, Foamboard delaminated. F, Felts cracked. N, No visible indentation. P, penetrated roofing. S, Coating shattered. —, Not tested.

the slag; "nests" of various sizes were left in the slag.

In summary, each roofing membrane performed better on the denser substrates than on the lighter substrates, the roofings made with inorganic felts performed better than those made with organic felts and the slag surfaced roofing was not damaged by hailstones up to and including 2½-in (6.4 cm) in diameter.

4.3. Nonbituminous Roofing

A number of nonbituminous roofings were tested for comparison purposes. These were applied in accordance with their supplier's recommendations. The levels of failure used in these evaluations were cracking for brittle roofings and objectionable indentations for metal roofing. Table 4 is a summary of the results of these tests.

TABLE 4. *Threshold of hail damage for nonbituminous roofing*

Description	Diameter of smallest hailstone causing damage					
	Edge		Center		Unsupported	
	in	*cm*	*in*	*cm*	*in*	*cm*
1/8-in (0.3 cm) Asbestos cement shingles	1 1/2	(3.8)	1 3/4	(4.5)	—	(4.5)
1/4-in (0.6 cm) Asbestos cement shingles	2	(5.1)	2	(5.1)	1 3/4	(4.5)
12 in x 18 in x 1/4 in (31 cm x 46 cm x 0.6 cm) Green slate, 7-in (18 cm) exposure	1 3/4	(4.5)	2	(5.1)	2	(5.1)
12 in x 18 in x 1/4 in (31 cm x 46 cm x 0.6 cm) Grey slate, 7-in (18 cm) exposure	—		2	(5.1)	1 1/2	(3.8)
1/2-in (1.3 cm) Cedar shingles—dry	—		1 1/2	(3.8)	1 3/4	(4.5)
1/2-in (1.3 cm) Cedar shingles—wet	—		1 1/2	(3.8)	1 1/2	(3.8)
3/4-in (1.9 cm) Red clay tile	—		2	(5.1)	1 3/4	(4.5)
Standing seam terne metal [a]						

[a] Dents proportional to hail size—visible for all hailstone sizes. The plywood deck cracked below the dents with hailstones larger than 2 1/2 in (6.4 cm).
—, Note tested.
All roofings tested were vulnerable to hail damage. As with the asphalt shingles, these other products contained areas of different vulnerability.

5. Conclusions

(a) All roofing materials have some resistance to hail damage, but as the size of the hail increases, a level of impact energy is reached at which damage occurs. This level lies in the area of 1½ to 2-in (3.8–5.1 cm) stones for most prepared roofings.

(b) Because of the ways in which prepared roofings are applied, most products have areas of different vulnerability.

(c) Heavier shingles tend to be more hail-resistance than Type 235 shingles.

(d) Weathering tends to lower the hail resistance of asphalt shingles.

(e) The solidly supported areas of roofing tend to be the most resistant to hail damage.

(f) Built-up roofs on hard substrates tend to resist hail better than those on soft substrates.

(g) Built-up roofs made with inorganic felts tend to be more hail resistant than those made with organic felts.

(h) Coarse aggregate surfacing tends to increase the hail resistance of roofing.

(i) The slate, asbestos cement and tile roofings tested contained areas of different vulnerability and cracked under the impact of 1½- to 2-in (3.8–5.1 cm) hailstones.

(j) The sheet metal roofing was dented by all sizes of hailstones used. Deck cracking occurred when 2½-in (6.4 cm) hailstones were used.

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